SERI/TR-632-812
UC CATEGORY: UC-62

AN ASSESSMENT OF EXISTING STUDIES OF WIND LOADING ON SOLAR COLLECTORS

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FEBRUARY 1981

PREPARED UNDER TASK NO. 3470.40

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Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

PREFACE

It is known that wind loading is the major structural design consideration in designing tracking and field-mounted solar collectors. The purpose of this report is to provide an assessment of the work done on the wind loading of solar collectors, investigate the commonality of findings in previous studies, examine remaining problem areas, and make recommendations to resolve those difficulties. This report should assist the designers and developers of solar collectors.

I would like to thank numerous individuals who provided me with their time and many fruitful discussions in support of this report. I would especially like to thank Professors Cermak and Peterka of Colorado State University, Duane Randall, Hal Post, Steve Peglow, and Bill Delameter of Sandia National Laboratories, and Bob Weaver of the Jet Propulsion Laboratory.

This work was supported by the Technology Development Branch, Division of Solar Thermal Energy Systems of the U.S. Department of Energy.

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SUMMARY

OBJECTIVE

This report provides an assessment of the work done on the wind loading of collectors for solar thermal applications and also for large field-mounted photovoltaic arrays. The commonality of previous work is investigated and recommendations are developed for the resolution of current uncertainties.

DISCUSSION

In developing solar collectors, wind loading is the major structural design consideration. Wind loading investigations have focused on establishing safe bounds for steady state loading and verifying rational but initial and conservative design approaches for the various solar collector concepts. As such, the effort has been very successful, and has contributed greatly to both the recognition and qualitative understanding of many of the physical phenomena involved. Loading coefficients corresponding to mean wind velocities have been derived to measure the expected structural loading on the various solar collectors. Much of the corresponding testing to arrive at those coefficients has been done in boundary layer test facilities, which model the natural boundary layer that individual collectors and fields of collectors are likely to encounter. A significant amount of this testing involves the study of fields of collectors and load-reducing barriers as well as shielding effects provided by adjacent collectors. The dynamic interaction problem has received very little attention to date.

CONCLUSIONS AND RECOMMENDATIONS

Although each specific design has unique detailed loading characteristics, there is a strong degree of correlation in the loading among the different solar concepts. One of the most significant consistencies apparent in all the tests is the benefit provided by fences and shielding provided by a large field of collectors. Taken in toto, these tests show that load reductions of three or possibly more seem feasible for an appropriately designed field and fence system. These potential benefits have not been claimed in any of the collector designs as yet. A more detailed quantitative understanding of the wind interactions phenomena within the field is however needed to take advantage of this potential.

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INTRODUCTION

Wind loading, especially on a structure with a large, exposed surface area, is a crucial design factor. Historically, wind loading has been an important concern in the safe construction of buildings and bridges. An excellent documentation of this field is presented in Refs. 1,2. Understanding of wind loading and designs to withstand that loading have evolved rapidly in the last 30 years or so, permitting the design of structures with a high assurance of safety. More recently, cost effectiveness and methods to optimally withstand windload have been the focus of much research.* To meet cost goals, new construction methods have resulted in lighter, more flexible structures with reduced damping. These new structures require an even greater understanding of wind loading to simultaneously guarantee structural integrity and economy as well as safety.

During the last five years, wind loading on solar collectors has been the subject of much concern and investigation. Safety problems associated with the potential collapse of bridges and buildings along with the likely attendant loss of life are not present. However, concern for protecting the frequently large capital investment of these systems is a priority, as is the need to meet stringent energy collection performance requirements. This has been especially true for tracking and other field-mounted collectors, where low cost and reliability for these repetitive structures are required. The effects of wind loading on these structures have been shown to be more severe than those caused by snow, rain, weight, earthquakes, thermal expansion, or any other environmental condition.

Wind forces are difficult to model for a tracking collector because for each orientation, a different loading condition can exist. Besides having to safely sustain maximum expected loads, a tracking collector must also be able to maintain its desired orientation within a certain accuracy band in typical wind environments and at minimum cost. Further, the weighting of these factors--survival or pointing accuracy--varies, depending on the needs of the specific collector.

Another technology receiving considerable attention is photovoltaics, where large field arrays of nontracking collectors are being proposed for central generation concepts.

Finally, loading on flat-plate nontracking collectors for heating and cooling applications has been the focus of a recent detailed study [4]. Wind loading on these collectors, which are usually mounted on buildings (though ground mounting is not rare) has typically not been a major concern. This is because the support structures for these applications are routinely overbuilt. However, concern for ensuring the integrity of glazings has arisen, and recent

*Reference [3] notes that more than 5000 papers have been published on wind forces since 1970.

findings have shown that support structures and mounting can lead to substantial costs, especially if additional roof reinforcing is required.

Wind loading on heliostats, parabolic troughs and dishes, and large-scale non-tracking photovoltaic arrays are discussed in this paper. The function of these concepts and their specific applications are discussed in many references [5,6,7,8], and schematics are shown in Fig. 1-1 of each collector concept. The four technologies not only have different design philosophies, but their various physical and deployment configurations lead to different loading conditions for similar wind speeds.

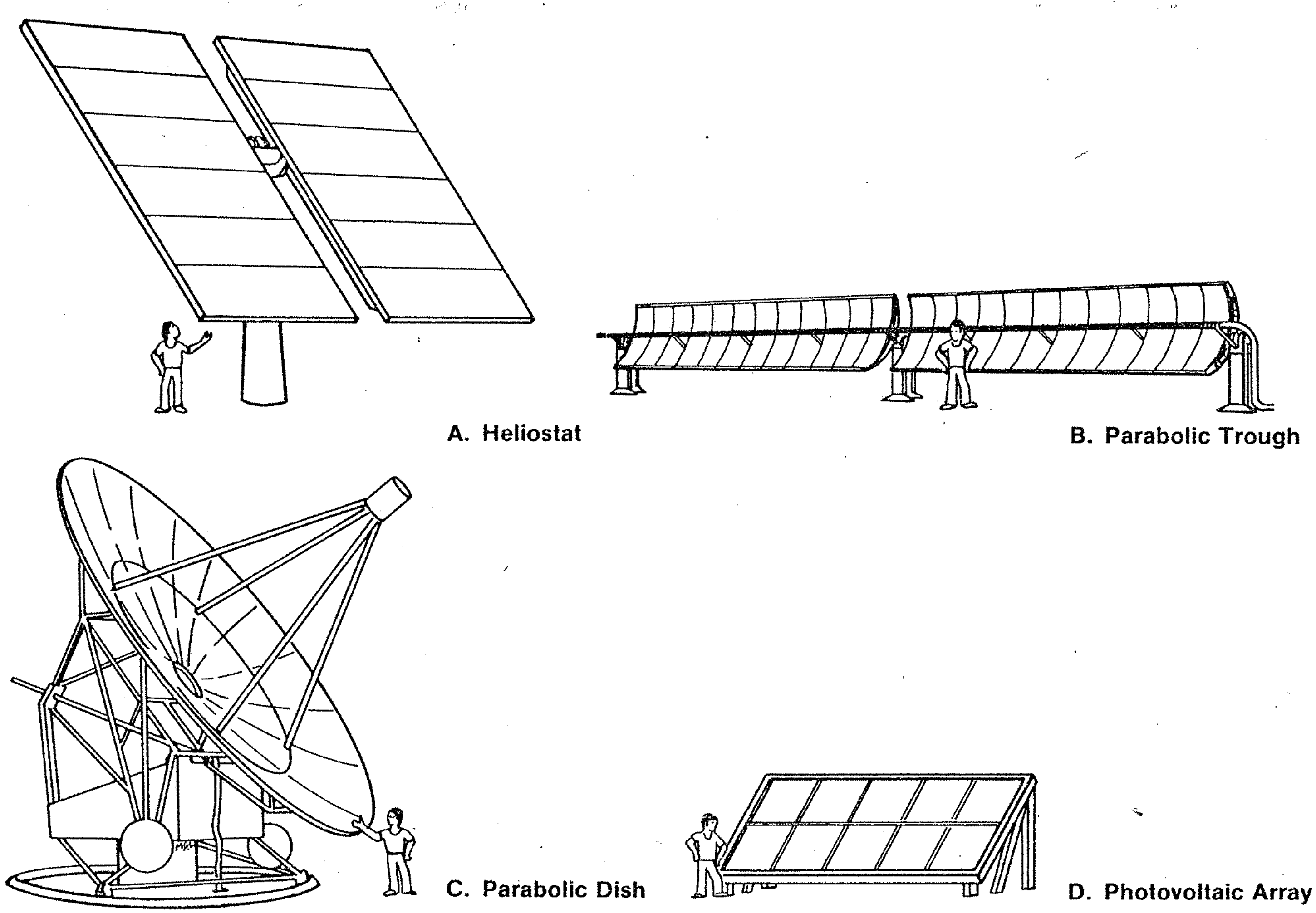

Figure 1-1. Typical Configurations Corresponding to Various Solar Collector Concepts

SECTION 2.0

CURRENT DESIGN APPROACHES

The most comprehensive (albeit at times conservative) design approach for wind loads used in the United States is ANSI A58.1-1972 [9],* developed by the American National Standards Institute. It was developed by a consensus approach and includes current practices, engineering knowledge, past experience, and synthesized research knowledge in the field. It is supported by extensive professional review and agreement and, as such, carries more weight than other kinds of standards. The ANSI standard has been adopted by the National Building Code in its entirety, but other U.S. building codes adopt only parts of it or other older standards [10]. The ANSI procedure has four basic steps, which in very simple terms are:

- determine a wind recurrence interval (e.g., frequency of the worst wind condition expected);
- determine a basic wind speed (e.g., the magnitude of that worst condition);
- determine effective pressures due to the basic wind speed (e.g., from charts or nomographs combined with equations); and
- determine pressure coefficients (e.g., again from charts or nomographs combined with equations).

The ANSI standard is a good starting point for designing solar collectors; however, strict application and adherence to it leads to several difficulties. First, the code (in its present form) states that the standard does not apply to structures of unusual shape. Next, since most of the standard was based on concern for life and safety rather than economic issues, the code is quite conservative [10]. Other indications of conservatism in the standard are that the wind velocity for elevations less than 10 m (33 ft) is assumed to be constant and equal to the velocity at 10 m, and that a 100-yr recurrence interval is recommended where life and safety are an issue. A 25-yr recurrence interval is recommended where safety is not an issue. Further,** the standard recommends designing for wind loading corresponding to the full approach flow, since load reductions due to shielding by other adjacent structures is not allowed. Wind tunnel data which addresses both shielding and channeling effects are allowed to supplement the code for special cases; however, specific guidelines in the generation of the data and its use are not given. The coefficients in the current standard appear somewhat conservative since most of them were obtained in smooth flow wind tunnels rather than in

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*This standard is currently under revision [11]. Modifications are suggested not only by standards committee members, but also by groups addressing particular issues of interest to industry [12].

**In a recent proposed form of the ANSI standard now under consideration, considerably more boundary layer wind tunnel data issued, and specific guidance for wind tunnel testing is given [11].

boundary layer tunnels (i.e., tunnels in which the expected natural boundary layer profile is modeled) [10]. Thus, additional procedures are needed in the design of solar collectors for wind loading.

Technical guidance for solar collectors from the national laboratories (since the vast majority of wind-related collector development is federally funded) has allowed significant flexibility in design procedures. Basically, the recommended approach combines information and guidance contained in the ANSI standard with supplemental information from wind tunnel data on an individual or case-by-case basis. The biggest problem facing collector developers has been that little wind loading data and knowledge specific to solar collectors has been available. Hence, to speed collector development, and to take into account data as it becomes available, the national laboratories have used an iterative, and interactive, consensus approach to evolve a set of "best estimates" of expected wind speeds to use for design purposes. Although there has been considerable interaction between the laboratories and the contractors involved within a particular solar technology, limited interchange across solar technology development has occurred. A common reason given for this apparent lack of coordination has been that each application is unique. This is a valid perspective, especially in the initial development stages. However, sufficient information is now becoming available that will assist all solar technologies. Table 2-1 shows critical design wind speeds currently being recommended for design purposes.

It should be noted that the various solar technologies have different design requirements and philosophies. For instance, survival in high winds is always an issue, but deformation under loading is a major concern with heliostats and dishes. In fact, for heliostats the high stiffness requirements to maintain the appropriate orientation usually result in a structure that can easily survive the worst storm condition in the stow configuration. With trough collectors, the pointing accuracy requirements during operation are more than an order of magnitude less than those for heliostats, and the controlling design condition is survival. With parabolic dishes, both pointing accuracy/tracking and survival appear to be equally crucial design drivers, but at the present the slew-to-stow condition is the major concern.

The bulk of the wind loading data gathered for the various solar technologies has focused on the most fundamental problem first; i.e., that of determining the loading induced by mean wind velocities. Structural and dynamic interaction problems have not been central in any of the numerous U.S. experimental studies; nor has the effect of gusts. However, as the need arises, the more complex dynamic problems are expected to be addressed in future work. A discussion of previous wind-loading studies follows.

Table 2-1. CRITERIA CURRENTLY IN USE FOR THE DESIGN OF SOLAR COLLECTORS

Collector Technology	Heliostats[a]	Troughs[b]	Dishes[c]	Photovoltaic[d] Arrays (Nontracking)
Maximum survival wind speed, m/s (mph)	(stowed) 40 (90)	(stowed) 35 (80)	(stowed) 44 (100)	Based on 100-yr mean recurrence at site
Design wind speed for normal operation, m/s (mph)	12 (27)	11 (25)	16 (36)	Based on 25-yr mean recurrence at site
Maximum wind speed during which collector must track, m/s (mph)	22 (50)	22 (50)	16 (36)	Not applicable
Stated or implied mean recurrence internal, yr	100 (extreme)	25 ground mounted 50 roof mounted (extreme)	100 (extreme)	25 (operating) 100 (extreme)

[a]Reference 13.
[b]Reference 14.
[c]Reference 15.
[d]Recommendation in Reference 16.

SECTION 3.0

METHODS OF DETERMINING WIND LOADING

Analytical work on bodies in airflow fields has been very limited, dealing mainly with simple geometric configurations and relatively low flow rates and corresponding Reynolds (Re) numbers. This is because of the complexities of turbulence and its interaction with structure. Thus, most work on airflow has been highly empirical. Unlike the aerodynamics of streamlined bodies, which is highly developed for aeronautical applications, the aerodynamics of bluff bodies in turbulent shear flows involves the nonlinear interaction of nonhomogeneous, nonuniform, turbulent approach-flow with three-dimensional turbulent boundary layers and separated flows over the body. None of these complex flow types is well described even when unperturbed by the others [2]. Therefore due to the number of variables, the results of a particular study are difficult to generalize; thus many studies are often needed to characterize all of the operative phenomena.

To date, considerable combined analytical and testing work on airflows around bluff bodies and flat plates in two dimensions has been done. More recently, data collection and analysis for complex three-dimensional flows has recently been directed at solar collectors [5,17,18,19]. Most experimental analyses have focused on a range of sizes from 1/60-scale to full-scale tests. The results of these analyses will be discussed below.

3.1 DATA PRESENTATION

In either full-scale or model experimental studies, data is usually taken so that loadings can be expressed in terms of force coefficients defined by

$$C_{FORCE} = \frac{FORCE}{qA}$$

$$C_{MOMENT} = \frac{MOMENT}{qA\ell} , \tag{1}$$

where $C_{()}$ is the coefficient, q is the "dynamic pressure," A is an appropriate area, and ℓ a characteristic length. The dynamic pressure q may be expressed by

$$q = \frac{1}{2}\rho u^2 ,$$

where

ρ = mass density of air stream [equal to 1.225 kg/m^3 (0.00238 slugs/ft^3) under standard conditions]

u = velocity.

Any consistent set of definitions may be used for A and ℓ. For example, an acceptable set of definitions is

	Heliostat	Trough	Dish
ℓ	Collector Height (H)	Collector Aperture Width (C)	Principal Dish Diameter D
A	H • Collector Width (W) = H • W	C • Collector Length (L) = C • L	$\frac{\pi D^2}{4}$

Because of excessive costs (associated with both the systems and components being tested as well as the scope of the available facilities), the use of subscale or model tests from which the loads on the full-scale device can be inferred is dictated. This can be done by using the laws of dynamic similarity and simulating the natural boundary layer winds in a wind tunnel in which the force coefficients would be identical for the model and prototype. Hence, in a valid simulation, results of the test can be scaled to the full-sized prototype by simply inverting Eq. 1. Thus,

$$\text{Force (Prototype)} = C_{FORCE}\,qA$$

$$\text{Moment (Prototype)} = C_{MOMENT}\,qA\ell^{*} \tag{2}$$

3.2 MODELING

Modeling is at best an approximation to reality since all of the phenomena that are operative cannot be simulated simultaneously. Thus, those aspects of the process that have the dominant effect on the system of interest are modeled most closely.

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*Care must be taken in assessing different studies, where the various precise definitions used for the moment arm and points of application must be clearly understood. Care must also be taken that the correct reference velocity is used. Sometimes the collector centerline is used [5,17,20], at times the 10-m (33-ft) height is used [16], and at times the top of the collector is used. For example, using a 1/7 power law for the velocity profile, and typical dimensions for a heliostat of 4.5 m (14.8 ft) for the midpoint, and 8 m (26 ft) for the top, the various drag coefficients expressed in terms of the coefficient at 10 m, $C_D(10)$, would be: $C_D(4.5) = 0.80\ C_D(10)$ and $C_D(8) = 0.94\ C_D(10)$. Further, some authors strongly urge the use of a reference height that is associated with the structure, since this procedure tends to remove the effects of mean velocity profile on the force or pressure coefficients (see [21]).

Accurately modeling the boundary layer requires that the vertical flow distribution and the turbulence intensity and spectrum in the wind tunnel match those at the site and that the Reynolds number (Re) of the model and the prototype be equal. In addition, the scale model must be geometrically similar to its prototype. If structural dynamic responses are to be modeled, structural stiffness (or elastic) similarity must also be maintained. A more detailed discussion of these requirements and their implementation in the wind tunnel environment is found in numerous references, such as [2]. The difficulties in modeling all parameters are very great, and compromises are often necessary. Further, there are relatively few* wind tunnel facilities capable of modeling the natural boundary layer winds at a specific site. There are, however, a significant number of facilities capable of performing aerodynamic loading on specific structures where the specific boundary layer structure is not important and only approximate total loads are required.

Usually the vertical velocity distribution profile of the flow velocity is modeled fairly closely. The vertical velocity profile can frequently be represented by a power law relation between the velocity u at a height Z and a reference velocity $u(z_o)$ at a reference height z_o:

$$u(Z) = u(Z_o) \left(\frac{Z}{Z_o}\right)^{1/n} ,$$

where n is an exponent dependent on the local terrain roughness and other effects such as buildings or trees. The reference height Z_o is usually taken to be 10 m (~33 ft), the height at which much meteorological data is gathered. Most of the boundary layer testing for solar collectors has been done with a profile typical of flat, open terrain (i.e., n = 7).** However, variations of this profile have been studied in at least one recent test series [16].

Reynolds number is usually not duplicated in many of the boundary layer wind tunnel tests, and it has never been matched in any of the subscale solar tests. This is because the required velocities would be typically too high (e.g., approaching sonic velocities) to be practical (e.g., for a 1/24-scale model, the model velocity would be 24 times the full-scale velocity). However, this is usually not considered important, except possibly in conditions where a curved collector pitches such that the leading edge is close to alignment with the stream. In Ref. 5, it was feared that at this angle the separation point could be strongly Reynolds number dependent, causing lift and

*Only four facilities in or near the United States are known to the author. The four are located at the Colorado State University in Fort Collins, Colo., the Virginia Polytechnical Institute in Blacksburg, Va., CALSPAN, in Buffalo, N.Y., and University of Western Ontario, Ontario, Canada.

**Typical values for 1/n are 0.28 for wooded areas and suburban locations, 0.4 for urban complexes [22].

pitching moment coefficient errors. This did not prove to be a significant problem with the tests for parabolic collectors, or any other collectors.

Researchers at Colorado State University [2,23] noted that there is usually a diminishing effect when Reynolds numbers exceed 15,000. To put this in perspective, in the full-scale test Reynolds numbers can exceed 10^7, and in the models they are often up to 10^5 (i.e., both significantly above 15,000). In addition, if the flow is extremely turbulent, the Reynolds number dependence is further minimized. Concurrence with this point of view was also reached on a recent heliostat study done in Japan [24]. On the other hand, Peglow [18] has shown a possible Re number dependence for the various scaled heliostat tests. His data shows variations of base moment coefficients of 0.62 at Re $\simeq 10^7$ to 0.94 at Re $\simeq 10^4$ (i.e., roughly a 50% increase going from the full scale down to 1/60th scale). There are, however, a number of possible differences that might explain this apparent dichotomy, including large differences in turbulence intensity factor, blockage [2,25] in the tunnel, and the boundary layer within the tunnel. Further, tests done on scale model photovoltaic arrays at different Re numbers show very small differences, but the range may be too small (4×10^4 to 20×10^4) to provide conclusive evidence. Thus the issue does not appear to be a moot point, and if greater precision is desired than that which is obtainable now, further investigation will be needed.

Turbulence intensity (TI) is defined as the root mean square of the flow velocity variations about the mean velocity (usually assumed to be free stream velocity) divided by the mean velocity. TI is usually expressed as a percentage, and a typical value is 20% (for a 1/7-power boundary layer). The consideration of TI can be important if the variations and distributions of pressure are important. Also, recent experiments on flat circular disks [32] show increases in mean base pressures for increases in turbulence. Further, the CSU people also call attention [16,19,22] to the fact that drag has been reported to increase with increased TI (at constant Re number).*

Even though the turbulence integral scale is not modeled exactly in small-scale tests, this may not be a significant problem [16,19], because the difference experienced by the prototype and the model is usually not large. Further, the prototype turbulence is often larger than in the wind tunnel, but the integral scale within the wind tunnel is 2-3 times longer than the model structure being tested.** For cases where an upstream collector disturbs the approach flow, differences in TI should result in a diminishing effect, since

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*It is interesting to note that if TI is held constant, and Re is varied, little or no change in drag is seen. However, this may not be true for all body shapes.

**The turbulence scale and spectrum modeled in the tunnel often correspond to subscales of 200-300. Further, the frequency spectrum during a test will typically correspond to short-duration (i.e., on the order of one hour) wind effects. Synoptic scale effects (i.e., extreme winds occurring once over several days or longer) are not modeled. However the effects of extreme winds can be inferred by using statistical methods with the test data.

the local TI will be dominated by the wake characteristics of the upstream object.

Finally it should be noted that wind tunnel tests generally investigate only the characteristics of mean wind loads. Gust effects have been considered to the extent that turbulent structure is adequately modeled. However dynamic aspects of the response are not modeled, nor are extreme gust loads. Dynamic response will be discussed later.

SECTION 4.0

TESTING RESULTS AND PLANNED TESTS

In the bulk of the testing done so far, the net loading on the solar collectors was determined experimentally using force balance techniques at the base of the structure to arrive at the aerodynamic loading coefficients defined by Eq. 1. Results of the testing done for the various concepts are presented below.

4.1 HELIOSTATS

Results from several recent works [6,19,26] indicate the present status of the testing and understanding of wind loading on heliostats. Specific generalizations from these tests are that

- From Ref. 6,* dynamic effects do not appear to play an important role in the survival capabilities of full-scale glass/metal types of heliostats. Thus the structure showed no severe airflow/structural dynamic interactions such as low-frequency vortex shedding. Further, the tests indicated that mechanically induced static displacement are greater than the dynamic values by more than an order of magnitude, although these tests [6] were performed for a limited number of orientations. However, discussions with CSU people [23] indicated that under certain conditions it was possible to induce coupled modes of dynamic interaction. In at least one model test at CSU a failure occurred of the model. It should be remembered, however, that structural strength and response similarity was not maintained in the model, and there is a possibility of an aggravated-turbulence-intensity effect in the model.
- From Refs. 6 and 19, a wind fence at the edge of a heliostat field may effectively lower the loads on the outer heliostats. Further, the data from Ref. 19 and discussions with the CSU people [23] indicate that a load reduction down to one third or possibly one fourth of the load without the fence looks feasible. Pitching moments and drag forces have been shown to reduce by 50%, up to an order of magnitude smaller than comparable no-fence cases. The fence height (~7 m full-scale), porosity (~30%), and distance to the nearest heliostat were selected such that the free streamline grazing the top of the fence could not impinge directly on the instrumented heliostat.
- The velocity profiles within a heliostat field are highly dependent on heliostat orientation and density [6,19].
- The effects of slots [19] between the heliostat mirror facets was found to be small in the range tested. However, the slot dimensions considered were very small (on the order of 1 or 2 in.) compared with the other heliostat dimensions.

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*Because of the limitations of the tests, generalizations from these results may not be appropriate. See also Section 6 of this report.

- The loads corresponding to the maximum uniform velocity flow (no gradient) of air on an individual heliostat can be accurately predicted by using a design code approach, such as that presented in the American Society of Civil Engineers, ASCE Paper No. 3269, Wind Forces on Structures [1].

- Results from a full-scale test [6] of a DOE prototype heliostat in the NASA, Ames, 40- by 80-foot facility were as expected even though the test did not attempt to model the natural boundary layer profile or the turbulence expected in the field. The heliostat, which is typical of state-of-the-art heliostat designs and is quite similar in design to the Barstow device, survived the full range of configurations and wind speeds currently specified for all heliostat designs with no damage to any of the components.

4.2 PARABOLIC TROUGHS

For parabolic troughs [5], two wind tunnel force and moment test series were conducted on parabolic trough solar collector configurations. The two test series were conducted in different flow field environments: a uniform-flow infinite airstream and a simulated atmospheric boundary layer flow, with the models simulating a ground-mounted installation. The force and moment characteristics of both isolated single-module troughs and of trough modules within array configurations have been defined over operational and stow attitudes. The data from the two series of tests are generally in good agreement except at particular attitudes where specific influences of the boundary layer velocity profile or ground effects assume particular significance with respect to the load characteristics. The influence of various geometric design parameters for collector modules and arrays has been established.

The results of these two test series have led to the following conclusions:

- The forces and moments on parabolic trough collector modules increase monotonically with mounting height above the ground.

- The peak forces and moments of individual collector modules increase with aspect ratio up to ratios of 10 or greater.

- Intermodule gaps as narrow as 6% of the aperture between end-to-end collectors within a row are sufficient to permit collectors to function aerodynamically as individual modules, effectively nullifying any long-row aspect-ratio influence.

- Collector modules installed within large arrays, even those within the second row of an array, experience an interference effect that provides a significant reduction (50%-60%) of the peak lateral and lift forces of the wind.

- The interference-induced load reduction does not extend to the collector pitching moment, indicating that a pressure distribution change accompanies the interference effect.

- Appropriate fence or berm configurations can provide reduction of lateral and lift forces in perimeter rows equivalent to the interference effect within collector arrays.

- A fence or berm height of approximately three-fourths the maximum collector height provides the major fraction of the force reduction achievable.
- The combined effects of boundary layer profile and ground blocking* are dramatically shown for pitching moment when compared with the smooth flow tunnel data.

4.3 PHOTOVOLTAIC ARRAYS

References 16 and 27 along with in-house work at both Sandia National Labs Albuquerque (SNLA) and the Jet Propulsion Laboratory (JPL) represent the latest effort in designing optimum structures for PV arrays. The results of these studies, for nontracking collectors, generally agree both qualitatively and quantitatively with the heliostat results. The Sandia method in conjunction with Bechtel [16] has been to define a rational and integrated approach to the design and optimization of PV collectors. The approach is similar to that suggested in the ANSI standard but it includes provisions for site wind investigations and a risk criterion similar to that used in power plants. The method developed by JPL and Boeing [27] is also an integrated approach, although the ANSI standard is not employed. Rather a combination of testing preceded by analysis, to determine the loads, is utilized in conjunction with an in-house (JPL) structural design and optimization effort, along with a reliability study. The basic conclusions from the wind loading portion of [16] are:

- The lift and drag coefficients of the arrays were shown to be related to the normal force coefficient, so that only the values of the normal force and pitching moment coefficients, CN and CMZ, are required for the design of the structural supports of the array.
- It appears that for the range of practical designs considered, neither the height above the ground nor the porosity of the array has a large effect on the aerodynamic coefficient.
- The effect of changing the individual array aspect ratio (i.e., between 2, 3, and 4) was not large.
- The reduction of the wind loadings on either individual arrays or on an array field by porous fences was very large. A 30% porosity fence with additional corner fence reduces the maximum value of $|CN| = 0.81$ to $|CN| = 0.33$ at the edges of the field and to 0.27 in the center of the field.
- In general, a solid fence was not as effective as a porous fence in reducing wind loading on structures.

In addition to showing consistency with [16], Refs. 27 and 29 have shown that

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*As the collector is pitched so that the bottom edge comes closer to the ground, the stagnation point can move down; tending to increase the moment, if the flow is restricted (or blocked) by the ground.

- Larger tilt angles for the arrays increase the protection to downwind arrays.
- The theoretical results over predict the loads experienced in the wind tunnel tests.
- Loads generated by uniform wind loads are fairly close to those obtained with boundary layer winds.

4.4 PARABOLIC DISHES

There is a wealth of design data for parabolic dishes corresponding to radio antennae and telescope applications [3,7,30]. Designs for these devices, which are not intended for mass deployment, have typically been very conservative, since their function required extreme reliability and accuracy. However, because of the many inherent differences in solar dishes, the applicability of this data must be questioned. The data for parabolic solar reflectors appears to be limited to extensions of these data. Further, most testing on parabolic dishes has been done for boundary layers that do not simulate atmospheric boundary layers. The author is not aware of field-effect and/or barrier studies of parabolic dishes for solar applications. However, because the data that is currently in use [31] appears at least qualitatively consistent with data from other solar technologies, much of what has been learned from these other technologies appears applicable. It is clear, though, that future testing should include testing of parabolic dishes, especially in the field.

4.5 FUTURE TESTING

There is a limited amount of testing being planned for the near future. With heliostats, field instrumentation for the Barstow facility is being investigated and planned for future field testing. At this point in time, wind velocity measurements at several points within the field are planned, and several heliostats will be instrumented with multiple load cells mounted under the mirror modules. This should result in a good indication of total loads as well as gross pressure distribution variations.

Parabolic troughs have been instrumented in the field at Willard N.Mex., to measure lateral and lift wind loading. Some of the inherent difficulties with field testing were encountered when only seven hours of applicable data were collected over a four month period due to the vagaries of the wind. The data has not yet been analyzed. On-site pressure distribution tests on troughs are now being planned for the Coolidge experiment in Arizona. Wind tunnel tests are also being planned to compare with the field tests.

The Boeing Co., under contract to the Jet Propulsion Laboratory, is currently [29] completing pressure distribution tests on photovoltaic arrays to confirm previous theoretical work [27] in support of their structural optimization efforts. Similarly, Sandia is planning pressure distribution tests to support their efforts.

SECTION 5.0

SOME COMPARISONS OF DATA ACROSS SOLAR TECHNOLOGIES

5.1 LOADS

It is interesting to compare data for the various solar configurations, along with data for the classical flat-plate shape given in Ref. 1. Table 5-1 (with Fig. 5-1) shows a comparison of lift, drag, and moment coefficients for various solar configurations along with the flat-plate data. It is seen that the coefficients vary most for lift and moment. For comparative purposes, the corresponding average drag-induced pressures on the various concepts are shown in Fig. 5-2.

The loads corresponding to the maximum uniform (no gradient) velocity flow of air on an individual heliostat [6] agreed with the design code approach such as that given in [1] this same generalization appears consistent with the data on photovoltaic arrays. Limited theoretical analysis [27,28] indicates qualitative agreement but significant overestimates of the laods occur as applied to photovoltaic arrays. This is due primarily to the inability to predict the correct pressures on the downwind side of the collector, which is in turn believed to be caused by ground effects.

5.2 COLLECTOR/FIELD CONFIGURATION - IMPACT ON LOADS

Testing performed to date indicates the potential for significant reductions of presently used design criteria. Results for modeled fields of heliostats, troughs, and PV arrays have shown significant load reductions on the drag and lift forces on nonperimeter collectors of the array and for all collectors when a fence or barrier is used.* This is consistent with classical theory of flow over a barrier (for example, see [27]): the barrier causes the stream to lift and reattach at some point downstream.** By protecting the first windward row of collectors from the free stream, subsequent rows can propagate the lifting of the free stream over the entire field. In general, the tests taken in toto show that drag and normal load reductions of a factor of three or possibly more seem feasible for an appropriately designed field and fence system. Significant reductions in pitching moments also seem attainable for heliostats, but moment reductions for troughs were not evident in the data.

The following results were demonstrated in the various tests:

- Fences: Fences are, in general, most effective for the nearest rows and provide shielding effects on a magnitude similar to internal array

*It should be noted that collector developers to date have not claimed a credit for possible force or moment design load reductions resulting from barriers or shielding.

**Films taken during many of the tests in which smoke was injected into the flow were often used to pinpoint areas where instrumentation would be most beneficial. Frequently these films also confirmed the expected flow patterns.

Table 5-1. TYPICAL EXPERIMENTALLY DETERMINED MAXIMUM FORCE AND MOMENT COEFFICIENTS FOR VARIOUS INDIVIDUAL SOLAR COLLECTORS SUBJECTED TO "STATIC" WIND LOADING[a,b]

Coefficient	Flat Plate [1]	Heliostat [6]	Trough [5][c]	Dish [7][d]
Lateral Load C_D (β = 0°)	1.2	1.18	1.44	1.5
C_D (β = 180°)	1.2	1.0	1.05	1.0
Lift Load C_L (β = 0°)	0.90 (α = 155°)	0.90 (α = 155°)	2.0 (α = 150°)	0.25–0.30[f]
	−0.90 (α = 35°)	−0.90 (α = 35°)	−1.2 (α = 30°)	−1.4 (α = 35°)
Moment Coefficient C_{M_Z} (β = 0°)	−0.12 (α = 30°)	−0.21 (α = 30°)	−0.30 (α = 45°, 180°)[e]	−0.05 (α = 40°)
C_M (β = 180°)	0.12 (α = −30°)	0.13 (α = 30°)	0.175 (α = 30°)[e]	+0.12 (α = 0°)

[a]See Fig. 5-1 for definitions of geometry and force directions.

[b]Moments are taken with respect to the attachment or pivot point, which for simplicity is assumed coincident with the center (in the heliostat case) or the surface apex (in the dish and trough cases). In real hardware cases, there will be some amount of offset, which must be carefully considered. Further, data very often is given for moments at the base of the structure. In this case, the resulting moments from the lift and lateral loads must also be considered. For example, see Ref. 6.

[c]90° rim angle length/aperature = 3.75.

[d]75° rim angle, dish depth/diameter = 0.20.

[e]These relatively high values for the pitching moment appear to be caused primarily by combination of boundary layer and ground effects.

[f]See Refs. 3 (pp. 294, 295) and 31 (pp. 3-48).

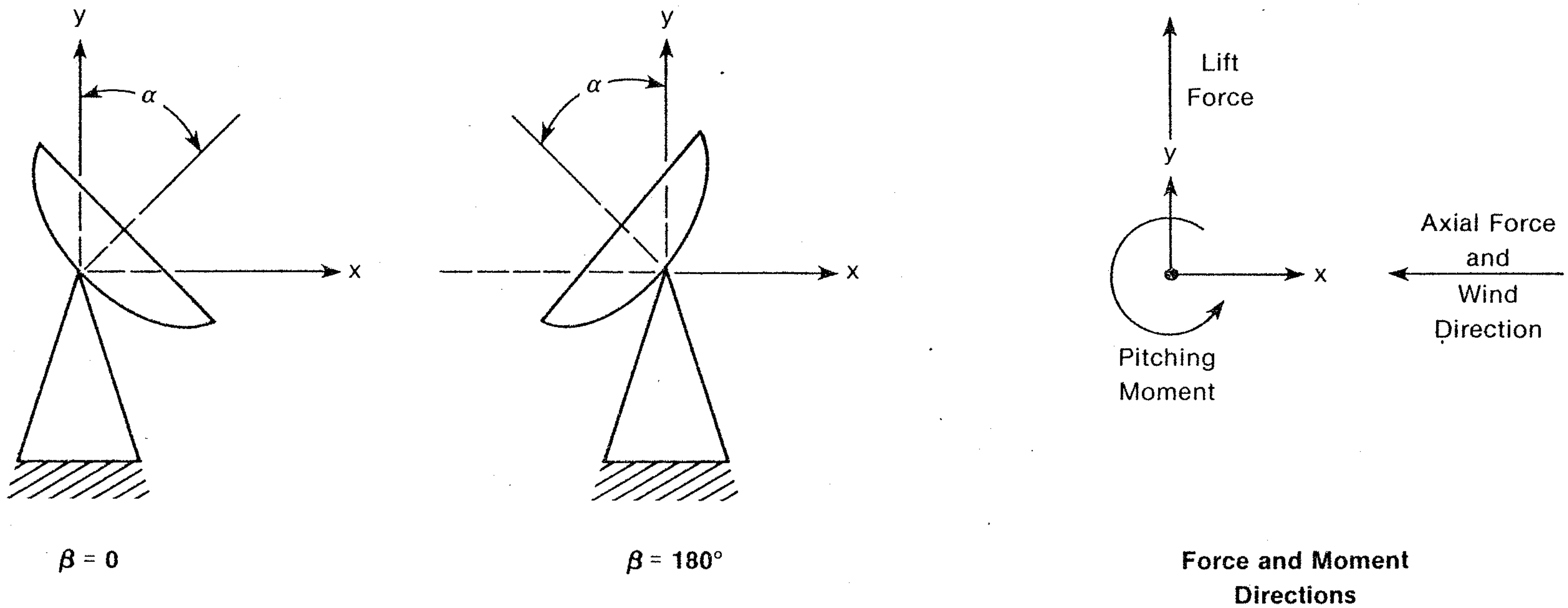
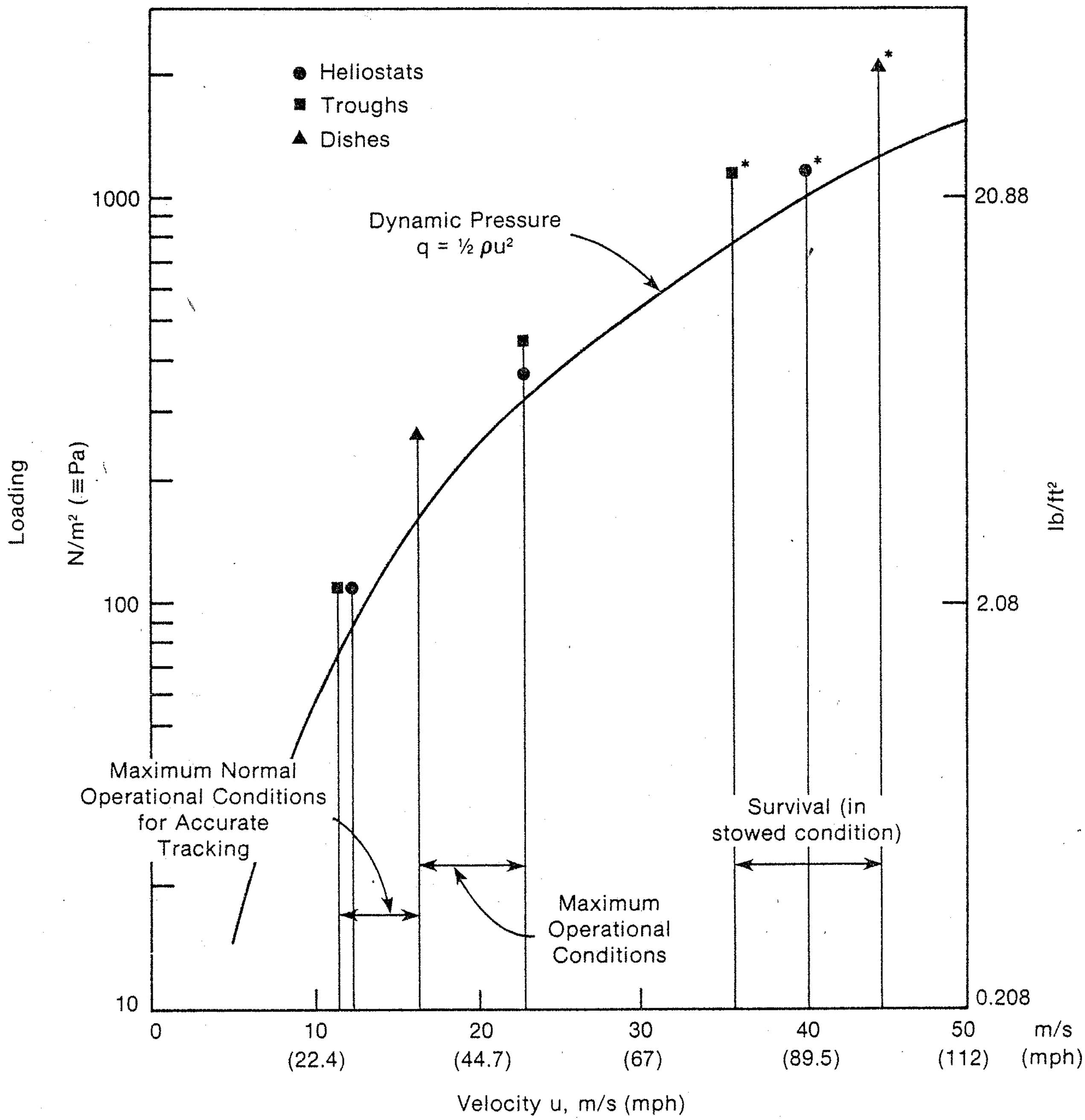


Figure 5-1. Definition of Geometry and Coordinates Used in Table 5-1



* These levels are shown for comparative purposes only and should not be reached in practice. In the stowed configuration, the load normal to the collector surface should be much lower.

Figure 5-2. Typical Dynamic Pressure and Maximum Drag Per Unit Area vs. Wind Speed Showing Typical Collector Design Criteria (Drag Coefficients from Table 5-1 are Used)

shielding [16,19,26].* Porous fences were more effective [16,26] than solid fences; the porosity tended to help break up the vortices behind the fence, and the solid fence at times tended to lift the stream such that the nearest arrays would be located within the vortex behind the fence. A porosity of somewhere between 30% and 40% seems optimal. Fences shorter than the center line of the collector were significantly less effective than higher ones, but few improvements were seen for fences much higher than 0.75-0.90 of the maximum collector height [5,16,27,32] for heliostats, troughs and PV arrays. Fences are less effective for abnormal winds [16] and sharp corners can cause vortex convergence (from the two sides), bringing higher momentum fluxes just inside the fence down onto collectors closest to the corner. This problem was eliminated in more recent testing by using fence junctions with less abrupt corners. Also, fences were shown to have some benefit of reducing channeling effects between rows of arrays [26]. For heliostats [19,26], pitching movements and drag forces were typically reduced by 50% or more (sometimes up to an order of magnitude). For PV arrays, the effect was somewhat more dramatic; reductions of 60% and more were seen [16]. The effect on troughs was similar to that for PV arrays as far as the normal forces go, but moments were not similarly reduced.

- Spacing effects: In general, both the shape and density of the array packing is significant. For heliostats and PV arrays, when arranged in rows, channeling effects were observed [26]. In Ref. 19, it was shown that if more than one heliostat obstructs the windward flow, 50% reductions in peak forces and movements were seen. Much less effect was seen when only one heliostat impeded the flow. One very noticeable effect in Ref. 26 was that the dense (70% GCR)** packing arrangement resulted in significantly higher ground turbulence as compared to the less-dense case (15% CCR). The turbulence intensities were often 60% and 25%, respectively.
- Tilt. The orientations of the various concepts corresponding to the maximum loading conditions are given in Table 4-1. Normal loads on the collector faces, increase with increasing angle of attack (bluff face windward) to a maximum at a 90° angle of attack (this also corresponds to the maximum drag condition). Also, according to [27], the larger angles of attack tend to increase protection for downwind arrays, by extending the wake regions in which large decreases in steady state flow velocity occur.

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*Individuals at Sandia (Livermore) have expressed the concern that fences and field protection may not ultimately significantly reduce the survival loads on the heliostats in the stow condition. This is because the heliostats located far from the towes are much more widely spaced than the close in heliostats. Further, the stow configuration offers the least wind resistance and least tendency to break up and mitigate the approaching boundary layer. These effects need more study. Their impact however will not be as significant with troughs, dishes, and fixed photovoltaic arrays.

**Typical average ground cover ratios (GCR) being used for solar thermal system studies are 22% for heliostats and 33% for both dishes and troughs.

- Slots and gaps. Slots and gaps up to 10% porosity in the array itself had minimal beneficial effects on heliostats and PV arrays [16,19]. A less than 10% decrease in normal force was seen for a 10% porosity. Gaps had a much greater impact on troughs. A gap of only 6% of the aperture width allowed the collectors to act independently (like an infinite gap). Porosities of up to 50% were investigated for parabolic dishes [7]. At this high porosity, a 25% decrease in the peak moment was observed and a 50% decrease in the peak axial force was observed.

- Aspect ratio. The effects of various aspect ratios for heliostats and PV arrays (where aspect ratios of 2, 3, and 4 were tried) was inconclusive [15]. With troughs that have the convex side windward, it appeared that an aspect ratio of 10 (collector length/collector aperture) resulted in forces and moments close to those for an infinite aspect ratio. With the concave side windward, troughs with aspect ratio of 10 still exhibited lower drag than that expected for an infinite aspect ratio.

- Collector height mounting: The effects of mounting PV collectors and troughs at different heights [5,16,20] were studied. In both cases the forces increased monotonically with height, and the rate of increase is fairly close to that expected due to the change in the velocity profile with height, but varied somewhat for various angles of attack. The normal force on PV arrays and the parabolic troughs at zero angle of attack both conformed quite closely to the height velocity relationship. The most dramatic impact of height appeared to be with the pitching moments on parabolic troughs. The data in Ref. 5 shows that the pitching moment (not moment coefficient) can change by more than a factor of four (decreasing in absolute value) as the height above the ground varies from 0.75 to 1.25 aperture widths. With further increases in height, the pitching moment appears to increase (absolute value) monotonically. This drastic variation in moment is probably caused by ground effects (e.g., blockage and increased turbulence), since in an ideal condition one would expect the moment to increase monotonically with height according to the boundary layer variation. This is consistent with other data in Ref. 5, where the maximum pitching moment measured in the boundary layer tunnel is three times larger than the corresponding moment in a smooth flow tunnel test. This last piece of data indicates the significant impact of the combined ground and boundary layer effects.

Clearly, the issue of load reduction is not totally resolved. Many of the test results are either only qualitative or at least very difficult to extend to collectors of any arbitrary configuration and placement. However, the results of the various tests are remarkably consistent and indicate that a very strong effort should be made to take advantage of both field configurations and fence effects in the design of solar collector systems.

SECTION 6.0

DYNAMIC TESTING

The majority of the wind tunnel tests on collectors have not yet addressed the dynamic-fluid structural-interaction problem. As stated earlier, the boundary layer tests in wind tunnels give a good representation of the mean velocity profiles and the resulting average loading coefficients corresponding to rigid structures. However, some dynamic aspects of the wind, such as extreme gusting, are not modeled, and the turbulence scale and spectrum is only approximated. Further, oscillatory motion of the structure induced by both periodic and aperiodic forces has not been modeled.

The dynamic response of the structure is important, since the fluid driving forces can occur at a frequency at or near one of the system's natural frequencies. If this occurs, damage and subsequent catastrophic collapse can occur. The major types of response induced in the structure depend on the nature of the fluid driving forces and can be categorized as vortex excitation, galloping excitation, flutter, gust, and wake buffeting excitation. In general all of these excitations, except for gust response, result in deformations that are perpendicular to the flow. Further, vortex excitation, flutter, and wake buffeting can be sustained and initiated in steady turbulent flow. Hence, although the dynamic modeling problem is significantly more complex than the static modeling problem, the opportunity exists for learning considerably more in wind tunnel facilities.* A brief description of common forms of each of these phenomena is given in Appendix A; details of simple examples can be found in basic engineering texts such as Refs. 3 and 33.

The Japanese study [24], which represents the only aeroelastic study so far on solar collectors, looked at both static and dynamic effects on heliostats in wind tunnel tests. No fences or barriers were considered, and static results agree very well with results from U.S. heliostat wind tunnel tests. The extension of their work into dynamic aspects provides additional insights. In their tests, static deformations were reduced by a factor of five for arrays as compared to single heliostats. On the other hand, the dynamic deflections (due to wake buffeting) were often five times greater for a multiple array as compared to a single heliostat. Still the worst static deflection (i.e., for a single heliostat) was about twice as large as the worst case dynamic deflection (i.e., for the array case), so field shielding appears to provide a significant benefit. These last results are also consistent with Peglow's [18] observation that the dynamic oscillations of a single full-scale heliostat (in a steady smooth-flow test) were an order of magnitude lower than the static deformations.**

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*Complications arise from the need to scale overall structure mass and stiffness with geometry, as well as the complications associated with modeling the microstructure of the wind.

**It should be noted however that this consistency may be somewhat fortuitous because of the vastly different test conditions (i.e., turbulence, scaling, etc.).

Modern numerical computer methods make most of the attendant structural problems readily tractable when the loads are known.* However, the detailed surface loadings and excitations are not often easily predicted, as explained earlier. Hence, for collectors, more sophisticated testing, incorporating the wealth of existing knowledge in the building industry, will probably have to be devised. An excellent description of applicable dynamic testing capabilities at the CSU facility is given in Ref. 22.

*Many of the collector designers have done dynamic analyses of their structure under assumed loading conditions.

SECTION 7.0

RECOMMENDATIONS

It is clear that there are many uncertainties yet to be resolved before we can accurately predict the loading on solar collectors. Because of the complexity of the problem, these uncertainties are not apt to be resolved totally or quickly. When considering small aggregations of solar collectors, it does not appear cost-effective to try to develop that understanding. However, the potential for reducing the design wind load on large collector fields by a factor of two or more can be quite attractive. Based on the consistency of the present data, it appears that barrier and field shielding may be an area where an understanding applicable to a number of solar technologies would be quite beneficial and feasible. Specific recommendations are that

- Field data on full-scale tests are needed to correlate and verify predictions derived from analysis and those inferred from results of subscale tests. There is no strong quantitative indication of either the adequacy or the degree of conservatism in current design approaches for wind loading. However, even though field information is limited, one has to be somewhat encouraged by the overall structural integrity exhibited by collectors in the field to date.
- The value of fences in reducing loads on collectors needs to be quantified to the extent that we can specify bounds on useful fence height, porosity, and distance from the field [6,19]. Also, for a low-density field, the possibility of internal fences or more closely packed rows should be investigated. This may take the form of additional testing preceded by appropriate cost trade-offs that consider options such as elimination of heliostats at the far edge (low-density) areas of the field, the additional blockage due to moving heliostats closer together to provide mutual protection, and the addition of fences within the field. Field-effect tests on existing facilities such as Barstow and the Sandia CRTF are being developed to correlate with wind tunnel tests.
- There is a discrepancy in the moment data between the small-scale and full-scale heliostat tests. This could be due to a Reynolds number effect and should be investigated to the extent of determining whether the trends within the data set for the small-scale tests are affected. It would be advisable to run a series of tests with several scale model sizes in the same facility over a range of Reynolds numbers.
- The full-scale wind tunnel tests performed on a McDonnel Douglas design heliostat were conducted with a uniform velocity profile. Scale tests for both uniform and power-law profiles are needed to check for repeatability and velocity profile dependence. Turbulence intensity may also be quite important.
- The predominant thought is that an exponent of 0.15, for instance, $V_h = V_{30} (h/30)^{0.15}$, should be used for open terrain. Data from the Sandia wind power facility at Albuquerque [18] indicates that this is a good average value, although it should be noted that this exponent varies as a function of wind speed, atmospheric stability, and surface roughness. Additional data from the field is needed to adequately bound this problem. This profile is relevant for the windward side of the field but

is totally inadequate internal to the field or behind the barrier. A way of correlating turbulence and boundary layer profile internal to the field with that of the approach flow is needed.

- The effects of gusts or increased turbulence internal to the field and the associated additional loading on the structures should be thoroughly understood, and guidelines should be developed to aid designers. This is especially important, since increased turbulence will tend to mitigate some of the mean load reduction benefits gained from fences and other barriers.
- Procedures to assess dynamic interactions between the wind stream and the reflector structures over a wide range of orientations and configurations need to be developed. This is because the power density spectrum of typical wind profiles shows considerable power available in the range that can excite natural frequencies in typical collector structures. These dynamic effects may also lessen some of the benefits from barriers and shielding.
- Many of the wind tunnel studies have been conducted at turbulence scales of 1:25 to 1:50 in boundary layers that are scaled in the range 1:200 to 1:500; the effects of which have not been examined. Additional study is needed to determine the influence of turbulence intensity and scale on aerodynamic coefficients of bluff bodies in a turbulent shear flow at the above scales.
- A more detailed analysis of existing solar collector wind tunnel data is needed to resolve apparent anomalies. For example, the relatively large rolling moments in the heliostat and trough tests are currently unexplained. Further, the wealth of conventional data related to buildings should be assessed for possible application to solar collectors, especially the data corresponding to gusting and other dynamic effects.
- Wind tunnel procedures for full-scale and model solar collectors should be standardized where feasible. For instance, standardized reference heights, turbulence intensity, profiles, etc., would allow easier comparison of data. Testing in facilities with similar characteristics would also minimize differences in tunnel effects such as blockage.
- A standard set of design approaches, or guidelines, should be settled on to aid all solar technologies. A risk criteria appropriate for solar, backed up by statistical analyses, and combined with weather studies at likely sites should also be developed. Proposed alterations to the ANSI standard that allow the designer to apply additional data and information should be supported.
- There currently is a paucity of experimental data particular to solar parabolic dishes, although some very old data for radar dishes is available. Field and fence effects with dishes have not been studied.

SECTION 8.0

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APPENDIX

A PHYSICAL DESCRIPTION OF SOME DYNAMIC WIND EFFECTS

VORTEX EXCITATION

Vortex excitation (whose direction is perpendicular to the flow direction) is caused by oscillations of vortices shedding in a periodic pattern on alternate sides of the body. The vortices are caused by the separation of the flow from the body and produce a low-pressure region just behind the separation point.

With smooth bodies in steady flow, the point of attachment changes with time, and the attachment and reattachment process is periodic. Since the low-pressure regions are produced with the same period as the formation of the vortices, a net force can result if the pressure forces are not balanced on both sides of the body. The frequency (N_s) with which this flow separation takes place is determined by the "Strouhal" relation and is explained in many texts, such as [33]. The Strouhal (S) number is given by

$$\frac{N_s D}{V} = S \quad , \tag{A-1}$$

where D is the cross wind dimension, and V is the mean velocity of the uniform flow. S, which is determined experimentally, depends on the body geometry and Reynolds number, and typical values for a bluff body are in the range 0.12-0.15. When one of the natural frequencies of the body equals the frequency (N_s) determined from the Strouhal relation, damage or catastrophic collapse of the body can result if the problem is not alleviated.

This phenomenon is observed quite frequently with long cylindrical structures such as smoke stacks and suspension bridge cables. From a practical perspective, there are numerous ways to alleviate or to eliminate the problem. Dampers, stakes, and shrouds have been frequently used to accomplish this [3].

Vortex shedding does not appear to be a major problem for solar collectors for a number of reasons. First, there are several ways to alleviate or eliminate regular vortex shedding if it does occur. Second, only flow that is edge-on to flat collectors appears capable of providing a sufficient driving force to support oscillations normal to both the flow and to the collector surface. However, the edge-on flow should result in limited regular periodic vortex shedding due to the dissimilarities between the front and back surfaces (i.e., caused by framing and other protuberances). The differences that will increase turbulence will, in turn, tend to abate the regularity of the flow and vortex excitation.

GALLOPING EXCITATIONS

As the name suggests, this kind of excitation is caused by an inherent instability. In this case, the force-velocity relationship is unstable. For wind loading problems, galloping excitations are caused when the velocity of the structure couples with the flow such that the net wind force is increased. This will occur if the angle of attack (resulting from the motion of the body relative to the wind stream) causes the wind loading to increase. An example of this phenomenon is given in Ref. 3 for a parabolic dish. Also in [3], Sachs gives a number of generalizations regarding galloping oscillations:

- Most simple shapes have an unstable characteristic at some attitude, except for a smooth circular cylinder.
- Galloping oscillations cannot start from rest. Wind gusts usually start structural movement, and oscillations then continue.
- The exciting force is small compared to that of vortex excitation. Stiff structures are not usually excited, and classic examples of oscillations are those of long flexible cables.
- The excitation occurs at all wind velocities. At low wind velocities, the relative wind angle is large, and at higher velocities the exciting force is increased. In fact, most galloping oscillations take place at low to medium wind speeds.

There is a considerable body of information on galloping oscillations of slender prismatic bodies [33], but limited application for structures similar to solar collectors has apparently taken place.

FLUTTER

Flutter is an aeroelastic dynamic instability. It is most commonly encountered when large aerodynamic loads occur lateral to the direction of flow. Flutter involves the dynamic coupling of more than one dynamic structural mode—usually the bending and torsion mode (e.g., as in the deck of a bridge or an airplane wing). For this coupling to occur, the deformation of the two modes must occur at the same frequency (called the critical flutter frequency). This implies that the two model frequencies must be fairly close to one another in the initial configuration so that small variations in geometry can make the two frequencies coincide. In Ref. 3, Sachs shows how the center of twist for a wing-like, flat-plate structure moves forward in a wind stream as the flow velocity increases. As the center of twist moves forward, the twist frequency also decreases, as would be expected, and eventually matches the plate bending frequency in the case tested.* At this point the elastic energy in either mode can easily transfer to the other mode, and an instability will result if the aerodynamic loads are such as to increase the twist moment. This can occur as shown in Sach's example if the twist center moves forward. However, if the rotational point were to move downstream rather than upstream the aerodynamic loading would tend to restore the wing to its undeformed state or damp the motion out.

*The twist center moves from its initial position because of aeroelastic effects. In effect the aeroelastic loads (which are functions of the flow velocity, the deformation, and rate of deformation) act as elastic stiffening elements.

For the general case, flutter is a complicated phenomenon that requires the solution of coupled dynamic equations in which relationships for the aerodynamic lift and moment must be known. The complication arises from the fact that the lift and moment are functions of the oscillatory frequency as well as angle of attack, geometry, velocity, and flow density. Thus the force and moment conditions are directly coupled in the eigenvalue equations. Complex eigenvalues result.

Flutter of aerodynamic bodies is fairly well understood, as it is the subject of a large mass of analytical and experimental information. The background of information for bluff bodies of arbitrary shape is quite limited, primarily because accurate lift and moment relations for these bodies do not exist. However, there is a significant amount of information on the flutter response of bridge decks [33] that may have application to flat solar collectors.

WAKE BUFFETING

Buffeting, which is not an aeroelastic or instability effect, is defined [33] as the unsteady loading of a structure by velocity fluctuations in the oncoming flow. If these velocity fluctuations are clearly associated with the turbulence shed in the wake of an upstream body, the unsteady loading is referred to as wake buffeting. Solar collectors in fields are all subject to wake buffeting, but effective analytical models for the random transient wake buffeting phenomenon do not exist. Hence, the solution of this problem seems most amenable to experimental and possibly statistical procedures.

Document Control Page	1. SERI Report No. TR-632-812	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle An Assessment of Existing Studies of Wind Loading on Solar Collectors	5. Publication Date November 1980 6.
7. Author(s) L. M. Murphy	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	10. Project/Task/Work Unit No. 3470.40 11. Contract (C) or Grant (G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)
In developing solar collectors, wind loading is the major structural design consideration. Wind loading investigations have focused on establishing safe bounds for steady state loading and verifying rational but initial and conservative design approaches for the various solar collector concepts. As such, the effort has been very successful, and has contributed greatly to both the recognition and qualitative understanding of many of the physical phenomena involved. Loading coefficients corresponding to mean wind velocities have been derived in these prior studies to measure the expected structural loading on the various solar collectors. This paper discusses current design and testing procedures for wind loading. The test results corresponding to numerous wind tests on heliostats, parabolic troughs, parabolic dishes, and field mounted photovoltaic arrays are discussed and the applicability of the findings across the various technologies is assessed. One of the most significant consistencies in the data from all of the technologies is the apparent benefit provided by fences and field shielding. Taken in toto, these data show that load reductions of three or possibly more seem feasible, though a more thorough understanding of the phenomena involved must be attained before this benefit can be realized. It is recommended that the required understanding be developed to take advantage of this benefit and that field tests be conducted to correlate with both analyses and tests.

17. Document Analysis
a. Descriptors

b. Identifiers/Open-Ended Terms

c. UC Categories

18. Availability Statement National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 43 20. Price $4.50

Form No. 8200-13 (6-79)